Continental Shelf Research 155 (2018) 45–51

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Recent coarsening of sediments on the southern Yangtze subaqueous delta front: A response to river damming

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ARTICLE INFO

Keywords:
Yangtze subaqueous delta
Dams
Sediment transport
Sediment coarsening
Sediment discharge
Accumulation/erosion

ABSTRACT

After more than 50,000 dams were built in the Yangtze basin, especially the Three Gorges Dam (TGD) in 2003, the sediment discharge to the East China Sea decreased from 470 Mt/yr before dams to the current level of ~140 Mt/yr. The delta sediment's response to this decline has interested many researchers. Based on a dataset of repeated samplings at 44 stations in this study, we compared the surficial sediment grain sizes in the southern Yangtze subaqueous delta front for two periods: pre-TGD (1982) and post-TGD (2012). External factors of the Yangtze River, including water discharge, sediment discharge and suspended sediment grain size, were analysed, as well as wind speed, tidal range and wave height of the coastal ocean. We found that the average median size of the sediments in the delta front coarsened from 8.0 μm in 1982 to 15.4 μm in 2012. This coarsening was accompanied by a decrease of clay components, better sorting and more positive skewness. Moreover, the delta morphology in the study area changed from an overall accretion of 1.0 cm/yr to an erosion of − 0.6 cm/yr. At the same time, the riverine sediment discharge decreased by 70%, and the riverine suspended sediment grain size increased from 8.4 μm to 10.5 μm. The annual wind speed and wave height slightly increased by 2% and 3%, respectively, and the tidal range showed no change trend. Considering the increased wind speed and wave height, there was no evidence that the capability of the China Coastal Current to transport sediment southward has declined in recent years. The sediment coarsening in the Yangtze delta front was thus mainly attributed to the delta's transition from accumulation to erosion which was originally generated by river damming. These findings have important implications for sediment change in many large deltaic systems due to worldwide human impacts.

1. Introduction

River estuaries are some of the most important areas where human societies originated and are still the most populated regions of modern society. However, resource utilization and man-made changes to the environment have reached unprecedented levels during the last 100 years. Many rivers around the world have suffered a serious decline in sediment discharge into the ocean, especially during the most recent 100 years, under the effects of reservoir construction, water diversion projects, and other factors (Milliman and Farnsworth, 2011; Syvitski et al., 2005; Walling, 2006). For example, the sediment discharge into the sea has now decreased to almost zero for the Nile River (Frihy et al., 2003; Stanley and Warne, 1998), the Colorado River (Carriquiry et al., 2001) and the Ebro River (Sanchez-Arcilla et al., 1998), and has decreased by approximately 70% for the Indus and Mississippi Rivers (Meade and Moody, 2010; Milliman and Farnsworth, 2011).

The Yangtze River (Fig. 1), the largest in China (> 6300 km long, ~900 km^3/year of water discharge, ~470 million tons per year, Mt/yr, of sediment discharge before decline), is now experiencing similar declines after the construction of more than 50,000 dams (Yang et al., 2006, 2011). Compared with the relatively stable water discharge since the 1950s, the sediment discharge has declined to less than 140 Mt/year because of intense human activities (Dai et al., 2008; Yang et al., 2014, 2015). The decrease in Yangtze's sediment discharge has been step-wised. Specifically, the sediment discharge decreased from 511 Mt/yr in the period 1956–1968 (prior to dam construction), to 450 Mt/

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https://doi.org/10.1016/j.csr.2018.01.012
Received 7 November 2017; Received in revised form 26 January 2018; Accepted 31 January 2018
Available online 02 February 2018

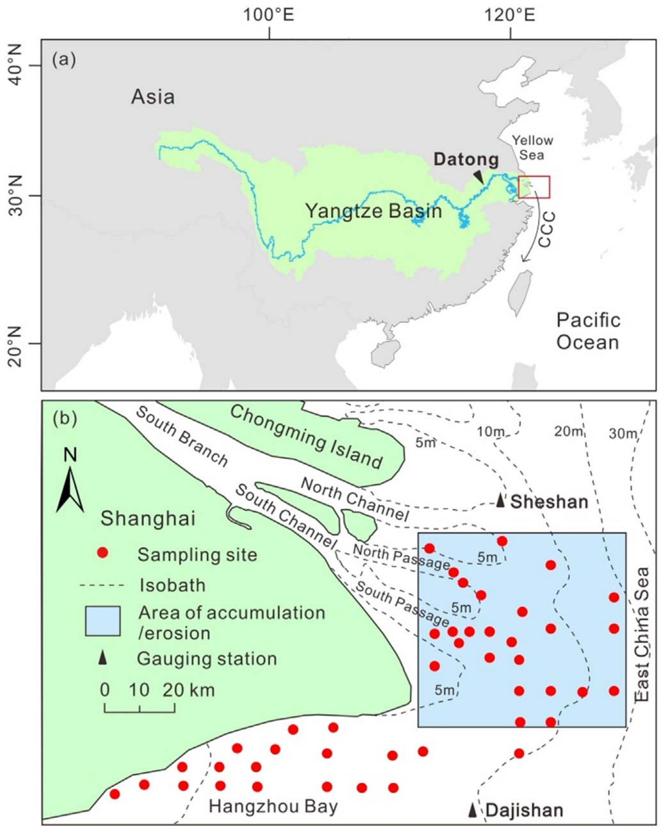

Fig. 1. Map of the locations of the Yangtze basin and the study area (a) and the surficial sediment sampling sites in 1982 (pre-TGD) and 2012 (post-TGD) (b). CCC: China Coastal Current. Isobaths are at 5, 10, 20 and 30 m.

yr in 1969–1985 (mainly due to construction of the Danjiangkou Dam), to 340 Mt/yr in 1986–2002 (because of dams constructed in the Jialingjiang, Minjiang and Wujiang tributaries and basin-wide soil conservation), then to 145 Mt/yr in 2003–2012 (mainly because of construction of the Three Gorges Dam), and finally to 118 Mt/yr in 2013–2015 (due to cascade dams constructed in the Jinshajiang River) (Yang et al., 2018). The Three Gorges Dam (TGD) is the world's largest dam and it was constructed on the main stem of the Yangtze River. 65% of the decrease in the fourth phase (Yang et al., 2014) and ~20% of the total decrease (Yang et al., 2018) were attributable to the TGD. The Yangtze estuary, especially the subaqueous delta front, is a zone sensitive to the decline in the sediment discharge, and some studies have been conducted in this estuary to evaluate its responses, such as deposition, erosion, and coarsening of sediments (Yang et al., 2011; Dai et al., 2014; Zhu et al., 2015; Luan et al., 2016). However, previous studies have mainly focused on the geomorphic responses of the subaqueous delta.

The outer part of the continental shelf off the Yangtze's mouth is relict Pleistocene sands, whereas the inner part is covered by modern Yangtze mud (Qin et al., 1987). Luo et al. (2012) found landward retreat of the sand-mud boundary and loss of clay depocenters in the subaqueous delta, and thereby inferred sediment coarsening. It was deduced that the mud, originally covered on the subaqueous delta margin, has now been eroded, and the relict sand below the surficial mud has been exposed (Luo et al., 2012). However, the study area of Luo et al. (2012) mainly focused on the region deeper than 20 m and lacked direct evidence from grain size data. It remains unknown if the coarsening occurred in the subaqueous delta shallower than 20 m. In this study, changes in sediment grain size were examined over a 30-year interval (between 1982 and 2012) in the southern Yangtze subaqueous delta (Fig. 1b). In addition, the external environmental contributing factors from both the Yangtze River and the ocean were investigated to help interpretations.

2. Study area

The Yangtze estuary is a large triple-bifurcating estuary with four outlets (Fig. 1). Currently, > 95% of the water and sediment discharges flow into the sea through the South Branch (Dai et al., 2016). When the sediment is transported to the Yangtze estuary, an Estuarine Turbidity Maximum zone forms in the mouth bar area because of the interactions between the sea and the river (GSICI, 1996). The mean tidal range and wave height at the river mouth are approximately 2.7 m and 1.0 m, respectively. The maximum tidal range and wave height are 4.6 m and 6.2 m, respectively (Hori et al., 2002; Yang et al., 2012). This region receives most of the upstream sediments, historically more than 470 Mt/yr (Milliman and Farnsworth, 2011), some of which cover the relict Pleistocene sands (Luo et al., 2012; Qin et al., 1987). However, approximately 150 Mt of sediments from the Yangtze River have been carried southward annually and deposited on the inner continental shelf by the China Coastal Current (CCC) (Fig. 1) (Milliman et al., 1985; Xu et al., 2012).

3. Materials and methods

3.1. Collection and analysis of surficial sediments

Forty-four surficial sediment samples in the Yangtze subaqueous southern delta were collected in March 1982 with a ship-based grab sampler and were repeated in the same locations in March 2012 (Fig. 1). To filter impacts of short-term (daily to seasonal) erosion and deposition on surface sediment grain size, we sampled sediments to a depth of 20 cm, which assumably reflected the yearly to decadal characteristics of surface sediments. Before the grain size analysis, the calcium carbonate and organic matter were removed from the sediments to avoid artifacts; then, the aggregated particles were disintegrated to obtain a well-dispersed soil suspension based on standard procedures (Van Doesburg, 1996). The sediment samples were then analysed for their grain sizes using sieve-pipette methods. The sediments were filtered using the sieve method to separate the coarser portions (coarser than 4 Φ) and to obtain their frequency distributions. The finer portions of the sediments were measured using the pipette method (Beuselinck et al., 1998). The size fractions of the sieve method and the pipette method were both 1 Φ. For consistency and to avoid processing errors, the same analytical method was applied for both 1982 and 2012 samples.

3.2. Geomorphic evolution analysis

To investigate the evolution of geomorphology in the Yangtze subaqueous delta, we accessed bathymetric maps at scales of 1:120,000 for 1979, 1986 and 2004 and of 1:150,000 for 2011 and no new bathymetric data were available after 2011. The bathymetric maps with a vertical precision of 0.1 m were compiled by the Maritime Safety Administration of the People's Republic of China. Grids with 30 × 30-m cells were created from these depth data using the Kriging interpolation method in ArcGIS. The areas of accretion/erosion were delineated and the thickness of accretion (positive) or erosion (negative) was calculated by the deduction of digitized maps with data of depth. After then, the total net volumes of accretion and erosion were counted up to calculate the annual vertical accretion/erosion rates.

The errors associated with the calculation in ArcGIS depended on the difference in depth between neighboring bathymetric data points and the complexity of seabed morphology. The error increases with neighboring difference in depth and the complexity of morphology (Yang et al., 2011). In this study, there were numerous digitized depth data points on each grid, which decreased the neighboring difference in depth. Besides, the slope of the seabed morphology is very gentle with